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High precision energy calibration with resonant depolarization at the VEPP-4M collider ☆

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Abstract

At the VEPP-4M collider the record accuracy of 10^{-6} of an absolute beam energy calibration was achieved with the resonant depolarization technique in the energy range including the J/ψ, $\psi(2S)$, $\psi(3770)$ resonances as well as the τ - lepton production threshold. This report discusses the methods, equipment and the results.

Keywords: VEPP-4M, KEDR, resonance depolarization, Touschek polarimeter, Compton backscattering, beam energy measurement

1. Introduction

VEPP-4M is a 366-m mono-ring collider with "two-on-two" electron and positron colliding bunches with four interaction points (Fig. 1) [1]. Three of them are parasitic ones where electrostatic separation of electron and positron orbits is applied. Collider ring is a part of the VEPP-4 complex, which also includes the Injector facility with the booster storage ring VEPP-3. VEPP-4M is designed for the center-of-mass energy range from 2 up to 10 GeV with the universal magnetic detector KEDR [2].

The program of the detector is focused on the study of $\psi-$, $\Upsilon-$ mesons and $\gamma\gamma$- physics. Since 2002 the goal of the first series of the experiments was precise mass measurements of J/ψ-, $\psi(2S)$- [3], $\psi(3770)$- [4], D- [5] mesons and τ lepton [6]. Such experiments are important because they test theoretical models and establish the bench marks on the mass scale of elementary particles as well as on the energy scale of the given collider. Also the data on masses help in an absolute calibration of momentum measurements in detector tracking systems.

In our experiments the resonant depolarization technique (RD) was applied for precise beam energy calibration. This report discusses the methods, equipment and the results.

2. Energy measurement methods at VEPP-4M

2.1. Resonant depolarization

Methodological support of physical experiments at VEPP-4 is maintained at a high level. The most precise method of the absolute measurement of the mean energy of particles at VEPP-4 is based on the resonant depolarization technique (RD), which was proposed and implemented for the first time at BINP [7]. This ap-

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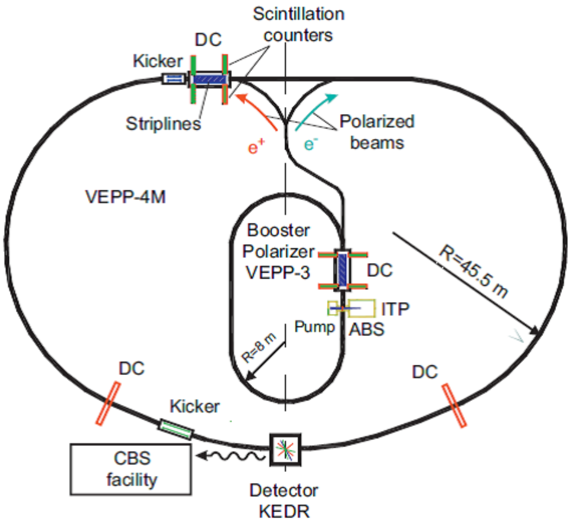


Figure 1: The VEPP-4 Complex with the elements of the Touschek polarimeter (*DC* , the counters of the distributed system of Touschek particle registration), the MØller polarimeter based on the internal polarized target (*ITP*), the depolarizer kickers as well as the Compton Back Scattering monitor (*CBS*).

proach was widely used thereafter both at BINP and in the laboratories throughout the world.

In an ideal storage ring with the planar orbits, the average energy of electrons in beam E is related to the average spin precession frequency Ω by the simple equation:

$$E = mc^2\gamma = mc^2 \cdot \frac{q_0}{q'} \cdot \left(\frac{\Omega}{\omega_0} - 1\right) = 440.64843(3) \cdot \nu\,[MeV],$$

with q' and q_0, the anomalous and normal parts of the gyromagnetic ratio; ω_0, the revolution frequency; $\nu = \gamma q'/q_0$, the spin tune parameter. Limitation of the accuracy of the energy determination by the spin frequency $\delta E/E \approx 7.8 \cdot 10^{-8}$ is due to errors in knowledge of the fundamental constants. To measure Ω one needs to have a polarized beam in a storage ring, a system to observe the beam polarization as well as a system for enforced beam depolarization at the external spin resonance.

A state of the VEPP-4M beam polarization at energies up to 2 GeV is observed by comparison of the Touschek electron/positron counting rate from the polarized and unpolarized bunches separated by a half turn (the "two bunch" method) [8]. It allows a significant reduction of the systematic errors related to variations of the beam lifetime and beam sizes. The system of scintillation counters installed at several azimuths and put into the dynamic aperture provides a total counting rate

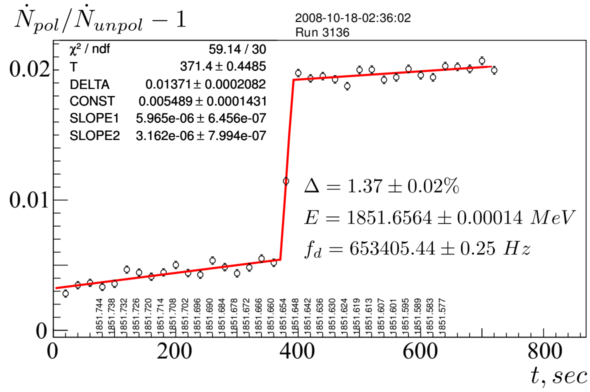


Figure 2: Depolarization jump in the ratio of the Touschek electron counting rates relating to the polarized bunch and the unpolarized one during the RD scan at a depolarizer frequency scanning rate (in a equivalent beam energy units) of about 300 eV/s .

$\sim$ 250 kHz/mA^2 at the distance of counters to the beam orbit of $\approx$ 1 cm. The relative counting rate experiences a jump of $\sim 1\%$ at the moment of depolarization proportional to squared level of polarization.

Two matched striplines of the VEPP-4 kicker are used to create a TEM wave propagating towards the beam. The signal source is a computer controlled frequency synthesizer [8]. The reference frequency signal for the synthesizer as well as for the VEPP-4M RF system is generated by the rubidium frequency standard (10^{-10}). Scan rate and the TEM wave amplitude are tuned to provide the depolarization time of $\sim$ 1 second. Typical behavior of the measured effect in time and the depolarization jump are shown in Fig. 2.

An absolute energy calibration accuracy by the RD method is of a record level: $\delta E/E \sim 10^{-6}$. It is determined by the spin tune spread $\delta\nu/\nu \sim 5 \cdot 10^{-7}$ due to quantum diffusion of particle trajectories in the presence of a quadratic non-linearity of the VEPP-4M guide field. To date more than 3500 RD calibrations have been performed.

2.2. CBS beam energy monitor

The instantaneous energy of a beam is measured by the RD method. But our measurements show that the VEPP-4M energy can vary during one day within a range of several tens of kiloelectron-volts, i.e., by a value of more than 10^{-5}. It is connected with both the magnetic cycles and the temperature instability of the ring (daily and seasonal). For monitoring the beam energy in the experiment with the accumulation of statistical data in the KEDR detector of VEPP-4M, as well as in some experiments at the Deuteron facility (VEPP-3), the method of Compton back scattering (CBS) is used.

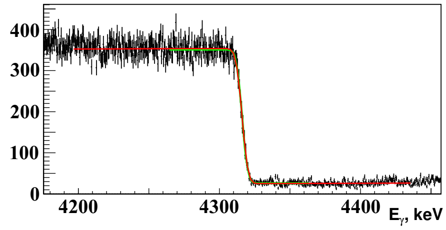


Figure 3: Fragment of the energy spectrum of backscattered photons measured by the HPGe detector.

The first beam energy measurements based on CBS were made at the BESSY-I and BESSY-II SR storage rings in Berlin. In 2005 this method was realized at VEPP-4M, for the first time for colliders [9]. Since then, it is a routine instrument for monitoring the VEPP-4M beam energy. At $E \leq 2$ GeV a record accuracy of about $5 \cdot 10^{-5}$ in determination of the energy was achieved by this method for a half an hour of scattered photon statistics acquisition. The method consists in measurement of the CBS spectrum edge (ω_{max}) related to the electron beam energy:

$$E = \frac{\omega_{max}}{2}\left(1 + \sqrt{1 + \frac{m^2}{\omega_{inc}\omega_{max}}}\right),$$

ω_{inc} is the incident photon energy. The infrared CO_2 laser with the 10.6 μm wave length and 50 W CW power is used for radiation generation. The laser spot size in the interaction area is approximately 10 times larger than the electron beam horizontal transverse size to provide a correct measurement of an average beam energy. Maximal energy of γ-quanta scattered towards the High Purity Germanium (HPGe) detector lies in the range 4-6 MeV. At first, the available γ-ray sources provided the HPGe energy scale calibration only in the 0.5 – 3 MeV range. Calibration at the 6000 keV edge was made by extrapolation of the low energy data or using RD data of the VEPP-4M energy. Extrapolation gave ~ 100 keV difference between CBS and RD energy measurements. At present, we have the 6.13 MeV γ-quanta source in conjunction with a precise pulse generator. It solves a problem of the independent energy scale calibration. In Fig. 3 the experimental spectrum is shown with the fitting applied to its edge. The "edge place" parameter is determined with a relative statistical accuracy $< 3 \cdot 10^{-5}$, while the "edge width" parameter has a statistical uncertainty of about 3%. These parameters together with the energy scale calibration are used to obtain the on-line data of the VEPP-4M beam energy and beam energy spread.

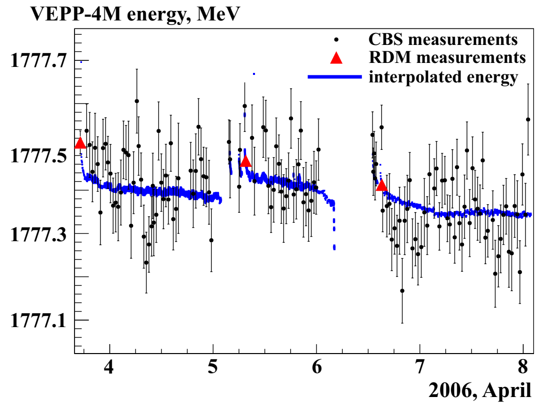


Figure 4: Joint energy measurements with RD and CBS in 2006 April runs. RD point markers are strongly increased in sizes to be more noticeable and do not correspond to a real uncertainty of the measurements.

The example of joint energy measurements by the RD and CBS methods performed during the tau mass measurement experiment is shown in Fig. 4.

3. Beam polarization

In the beam energy range 1.5 ÷ 1.9 GeV the VEPP-3 booster storage ring serves as a source of polarized particles for the VEPP-4M collider. The energy scaling of the radiative polarization time at VEPP-3 and VEPP-4M as well as the values of this parameter at two characteristic energies are presented in Tab. 1. There is no possibility to obtain the polarization directly in the collider at the mentioned energies. In the case of injection of the polarized beam from the booster a positive fact is a large radiative relaxation time of the depolarization processes related to the VEPP-4M field imperfections. Using the new method [10] developed by us and based on measuring the asymmetry in scattering of polarized beam electrons on the internal target of the thickness of ~ 5×10^{11} electron/cm^2 formed by the jet of polarized deuterium atoms from the Atomic Beam Source of Deuteron Facility we studied the radiative polarization

Ring	VEPP-3	VEPP-4M
Scaling with Beam Energy (τ_p[h], E[GeV])	$\tau_p = \frac{12}{E^5}$	$\tau_p = \frac{1540}{E^5}$
τ_p@1.55 GeV	1.34 h	172 h
τ_p@1.85 GeV	33 min	70 h

Table 1: The Sokolov-Ternov polarization time.

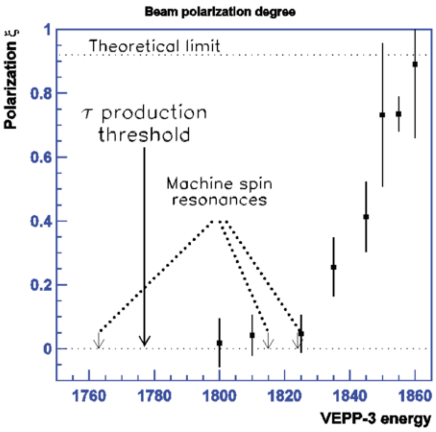


Figure 5: Measured beam polarization vs. the VEPP-3 energy. The spin resonances marked are:$E \approx 1815$ MeV ($\nu_x - \nu = 1$), $E \approx 1825$ MeV ($\nu_y - \nu = 1$) and $E = 1763$ MeV ($\nu = 4$, the integer resonance)

extent achieved at VEPP-3 in the beam energy region near the tau production threshold and the $\psi(2S)$ peak (see Fig. 5).

The important result was an observation of the significant depolarizing influence of the spin resonances associated with the spin ($\nu = \gamma a$, $a = (g-2)/2$) and betatron (ν_x, ν_y) tunes. The polarization appeared to be small in a wide range below 1840 MeV down to the τ production threshold. Taking into account this result we injected the polarized beam into VEPP-4M at 1850 MeV and then deaccelerated the beam down to the τ threshold where the RD technique was applied for the τ mass measurement. In the energy region of the J/psi -resonance there is no problems with obtaining the polarization at VEPP-3. During the radiative polarization process the special system automatically controls the VEPP-3 betatron tune working point keeping it far enough from the dangerous combination spin resonances. In practice, the time spent for polarization is noticeably less than $2.5\tau_p$ (see Tab 1) and makes up 5000 s and 2000 s at 1.55 GeV and 1.85 GeV respectively. The resulting polarization extent is still sufficient for precise energy calibration with the RD technique.

The vertical spin projection of polarized positrons injected at 1.85 GeV is 1.5 times less than that of electrons (having the analogous projection close to 1). It gives a design decrease of depolarization jump in the RD technique by a factor of 2.5. With the aim to eliminate this defect, we installed and applied the 2.5 T·m pulse solenoid at the VEPP-3-VEPP-4M beam-line section before the outlet 90° bend magnets. As a result, the

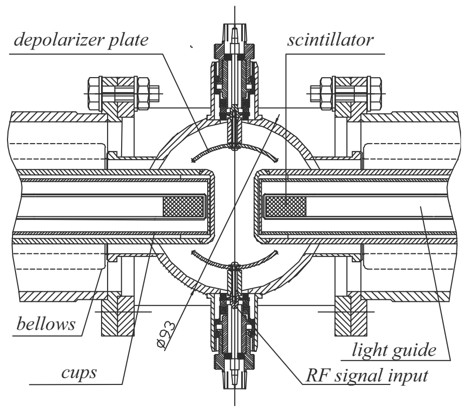


Figure 6: Construction of the Touschek polarimeter insertion with scintillator counters and depolarizer plates.

depolarization jump for positrons increased by a factor of 2. This contributed to improvement of an accuracy in the electron-positron energy gap measurement ($\sim$ 1 keV), which is important for the systematic error study.

4. Touschek polarimeter

There are three Touschek polarimeter insertions at the VEPP-4M ring. The transverse cross-section of the vacuum chamber in one of these insertions containing the scintillation counters and depolarizer plates are shown in Fig. 6. Scintillation counters can be moved towards a beam orbit with the help of stepper motors. The shown Touschek insertion is installed at the VEPP-4M technical section. Two more TEM wave-based depolarizers and two scintillation counter pairs are used separately at different azimuths of the ring in the experimental hall.

The plot in Fig. 7 demonstrates the calculated and measured dependences of counting rate on a distance from the counter to orbit position. We measured the Touschek counting rate in a wide range of VEPP-4M energy (Fig. 8). The resulting energy dependence normalized on a beam volume and a square of bunch current differs a little from the theoretical one $\propto E^{-3}$ in the power index. The assumed reasons of this discrepancy are inhomogeneity of the experimental conditions with changing energy and uncertainty in definition of the effective beam angular spread [11].

Also we experimentally studied a behavior of depolarization jump magnitude with changing betatron coupling in comparison with the theoretical calculations [11] (Fig. 9). According to our estimation the depolarization effect in the counting rate of the Touschek parti-

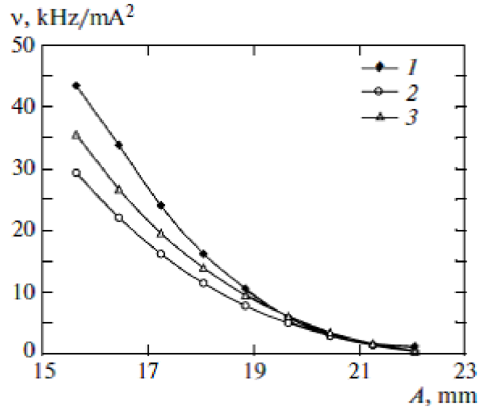


Figure 7: (1) Measured and (2,3) calculated counting rates of the scintillation counter versus the distance between the counter and beam orbit (A). The parameters of calculation are the 1.1% energy aperture and the betatron coupling coefficient (the ratio of the vertical and horizontal emittances) of $\mathcal{E}_y/\mathcal{E}_x \approx 0.033$ (the curve 2) and ≈ 0.028 (the curve 3). The parameters of the experiment are $E = 1.55$ GeV and the beam current $I = 3.0 \rightarrow 2.8$ mA.

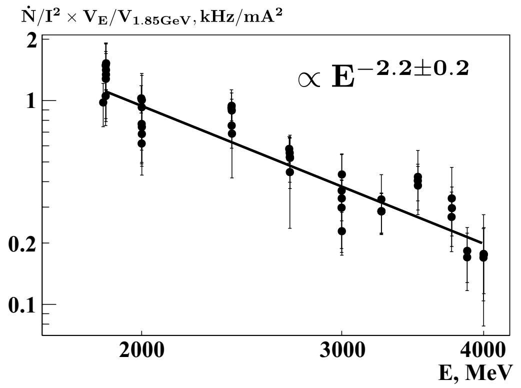


Figure 8: Measured energy dependence of the normalized counting rate of Touschek electrons $\propto E^{-2.2\pm0.2}/V_b$, where V_b is a beam volume.

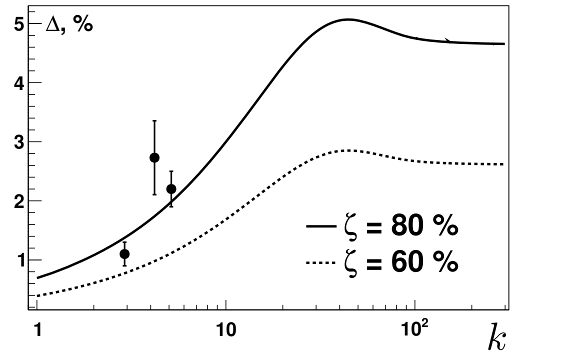


Figure 9: Calculated jump versus the "inverse" coupling parameter $k \approx \sqrt{\mathcal{E}_x/\mathcal{E}_y}$ for two polarization degrees at $E = 1.85$ GeV. The points are the measured values of the depolarization effect.

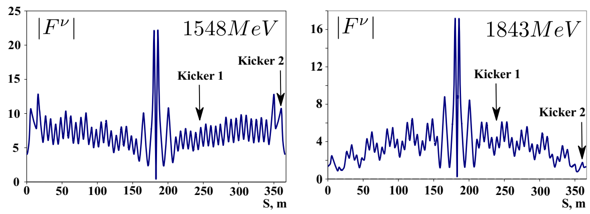


Figure 10: Spin Response Function F^ν for $E = 1548MeV$(left) and $E = 1843MeV$ (right) versus the VEPP-4M azimuth [13]. The rate of resonant depolarization is $\tau_d^{-1} \propto \varphi_\perp^2 |F^\nu|^2$. At one passage of the depolarizer the spin rotation angle is $\varphi_\perp$. Spin Response Function F^ν takes into account a depolarization effect of vertical betatron oscillations exited by the depolarizer kick. In different cases $|F^\nu|^2$ may be < 1 or achieve $\sim 10^2$ and more.

cles decreases with an increase of the energy as E^{-4}. Because of a slump in the counting rate and depolarization jump the Touschek polarimeter becomes non-relevant at the VEPP-4M energies above 4 GeV.

5. Tuning of depolarizer

Efficiency of depolarizer is determined through the so-called spin response factor [12] which depends on azimuth of its location and beam energy and can vary through several orders (Fig. 10). This fact influences a choice of a depolarizer location (compare the factor values of two kickers at different azimuths in Fig. 10).

Also, the efficiency depends on a rate of frequency scan. Accurate tuning of depolarizer is important because of a danger of the spin sideband resonances $\nu + l \cdot \nu_H \pm \nu_d = k$ related to the guide field ripples $H = \bar{H} + \Delta H \cos \nu_H \theta$ (ν_d is the depolarizer frequency in the units of ω_0). The 50 Hz ripples at $\Delta H/H = 20$ ppm can lead to a systematic error of 1.5×10^{-5} ($E = 1.85$ GeV) in energy determination because of small difference between the depolarization rates at the first modulation and main external spin resonances (see Fig. 11) [13]. To avoid the error caused by depolarization at the modulation spin resonances we thoroughly calculate the depolarizer efficiency and properly tune the scan mode. In practice, we suppressed the ripples in the VEPP-4M field to below a 10 ppm level that yields $\tau^{(1)}/\tau_0 \approx 8$. For comparison, at the hypothetical FCC storage ring with a 90 km perimeter the 50 Hz ripples at $E = 45$ GeV mean a significant systematic error of 6.5 MeV (1.45×10^{-4}), which, nevertheless is unlikely to be admitted because of a rather large assumed ratio $\tau^{(1)}/\tau_0 \approx 10^3$ at $\Delta H/H \sim 10$ ppm.

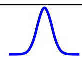
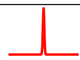
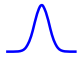
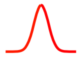
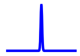
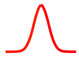
Type	W_k	dE/dt, kev/sec	σ_E, keV	ΔE, keV	Relative width σ_d	σ_s
"CLUB"	10^{-6}	10	2.1	10		
"J/ψ"	$5 \cdot 10^{-7}$	0.3	0.4	2		
"CPT"	$4 \cdot 10^{-8}$	0.005	0.05	0.002		

Table 2: Operation modes of the depolarizer. "CLUB": quick energy calibrations in regions of a resonance substructure. "J/ψ": the most precise calibrations in narrow resonance peaks. "CPT": a precise comparison of the spin frequencies of electron and positron. W_k is the resonant harmonic amplitude [12] of a perturbation generated by the depolarizer; dE/dt is the scan rate; σ_E is the dynamic widening of the depolarizer line; ΔE is the spin frequency resolution.

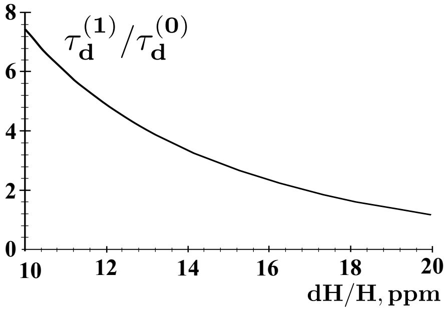


Figure 11: Ratio of the depolarization times at the first modulation and main spin resonances ($l = 1$ and $l = 0$) versus the relative amplitude of the 50 Hz guide field ripples.

The Tab. 2 illustrates three main scan modes we use. An interesting detail is seen in the scan (Fig. 12) with the highest resolution in depolarization frequency (2×10^{-9}) [14, 15]. Width of a long-drawn depolarization jump corresponds to the spin line width in a beam estimated as 5×10^{-7}.

The experiment on the thrice-repeated partial depolarization with changing scan direction demonstrates correctness of our tuning (Fig. 13). All three measured energy values are in the 6 keV interval (3×10^{-6}), which could be caused by the guide field drift.

6. Accuracy and stability

Questions of accuracy concern the determination of the mean energy of each of the colliding beams, the determination of the center-of-mass energy as well as the energy stability. Various sources of systematic errors listed here were analyzed [16, 17, 18, 19, 20].

- Groups of error sources:
  - a mean energy value determination basing on a

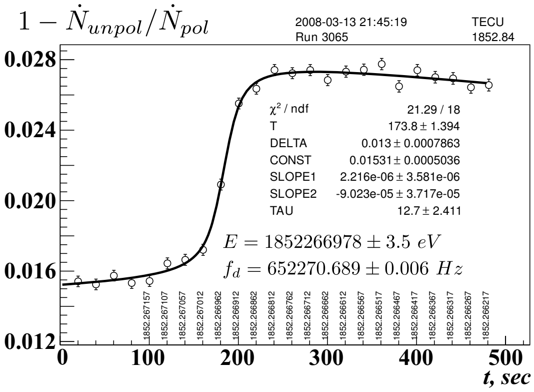


Figure 12: Depolarization process at fine scanning with a rate of 2.5 eV/s and with a depolarization frequency resolution of 2×10^{-9}. The depolarization jump is "long-drawn" due to the sensitivity of fine scanning to the spin frequency spread of 5×10^{-7} in a beam.

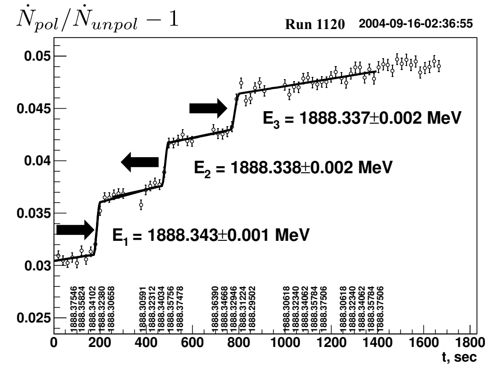


Figure 13: The process of the three-fold RD energy calibration using the method of partial depolarization of one and the same beam. The scan direction (up or down in frequency) was changed after every next depolarization jump.

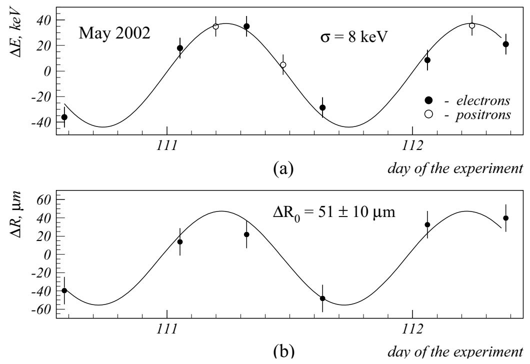


Figure 14: Correlation of the daily energy oscillations with the mean orbit radius deviations measured by BPMs.

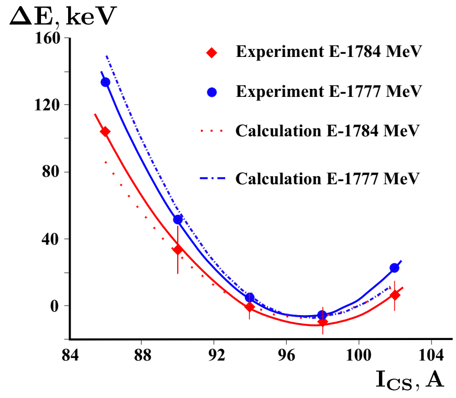


Figure 15: Measured and calculated spin tune shifts related to decompensation of the KEDR field.

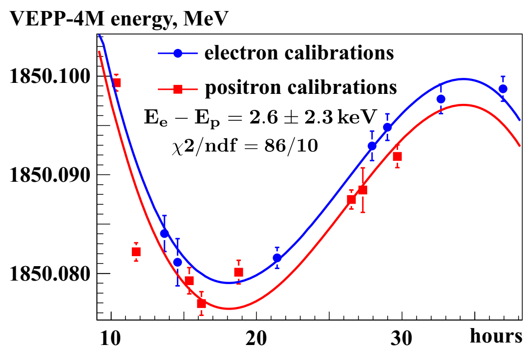


Figure 16: Distinct-in-time comparison of electron and positron beam energies. The measurements in the series of consecutive energy calibrations with electrostatic orbit bumps turned on.

measured spin frequency;
- an energy stability in time domains between energy calibrations;
- determination of the produced particles energy in a Center-of-Mass system basing on an energy of one of colliding beams measured with RD.

- Methods of accounting:
  - correction of measurement data;
  - declaration of uncertainty.

- Sources of errors:
  - radial orbit distortions (non-stability of currents in magnet coils, temperature variations, geomagnetic storms, solar and lunar daily geomagnetic variations *etc*);
  - vertical orbit bumps at the sections without bend magnets;
  - a violation of the simple energy-spin tune relation (the random perturbations of vertical orbit, the weak longitudinal magnetic fields, the vertical orbit bumps at the sections with bend magnets);
  - an azimuthal dependence of beam energy due to radiative losses;
  - effect of beam parameters in IP (a momentum spread, an inaccurate colliding beam convergence, a parasitic vertical dispersion, the VEPP-4M Final Focus (FF) chromaticity, a beam potential *etc*).

In the beginning of our experiments with RD we revealed significant daily energy oscillations (Fig. 14) which were diminished by an order later on. Inaccurate compensation of the longitudinal magnetic field of the KEDR detector can lead to significant error in energy determination by spin frequency. We measured the dependence of the spin tune shift on the anti-solenoid current. In minimum it yields an optimal ratio of the main and compensating fields of the detector (Fig. 15). Thus the betatron coupling (down to $\sim 1\%$ in the anti-solenoid current) and the systematic energy error (down to ~ 1 keV) are minimized.

Special experiments on the distinct-in-time comparison of electron and positron energies (Fig. 16) as well as on the simultaneous measurements of these beams energies demonstrated that a difference between electron and positron energies makes up a value of the order of 1 keV due to electrostatic orbit separation in parasitic IPs in accordance with the estimations.

7. Mass measurements at VEPP-4M

The VEPP-4 Complex has the richest history of mass measurement experiments in comparison with other laboratories (Tab. 3). In the new series of such experiments at the modernized collider VEPP-4M an accuracy

Particle	M, MeV	Accuracy $\Delta E/E$	Detector	Years
J/ψ	3096.93 ± 0.1	$3.2 \cdot 10^{-5}$	OLYA	1979-1980
$\psi(2S)$	3685.00 ± 0.12	$3.3 \cdot 10^{-5}$	OLYA	1979-1980
Υ	$9460.57 \pm 0.09 \pm 0.05$	$1.2 \cdot 10^{-5}$	MD-1	1983-1985
$\Upsilon(2S)$	10023.5 ± 0.5	$5.0 \cdot 10^{-5}$	MD-1	1983-1985
$\Upsilon(3S)$	10355.2 ± 0.5	$4.8 \cdot 10^{-5}$	MD-1	1983-1985
J/ψ	$3096.917 \pm 0.010 \pm 0.007$	$3.5 \cdot 10^{-6}$	KEDR	2002-2008
$\psi(2S)$	$3686.119 \pm 0.006 \pm 0.010$	$3.0 \cdot 10^{-6}$	KEDR	2002-2008
$\psi(3770)$	$3772.9 \pm 0.05 \pm 0.06$	$2.1 \cdot 10^{-4}$	KEDR	2002-2008
D^0	$1865.43 \pm 0.6 \pm 0.38$	$3.8 \cdot 10^{-4}$	KEDR	2002-2008
D^+	$1863.39 \pm 0.45 \pm 0.29$	$2.9 \cdot 10^{-4}$	KEDR	2002-2008
τ	$1776.69^{+0.17}_{-0.19} \pm 0.15$	$1.3 \cdot 10^{-4}$	KEDR	2002-2008

Table 3: Mass measurements at VEPP-4: history

of the mass measurement of the charmed mesons J/ψ and $\psi(2S)$ was improved by several times. At present, masses of only five elementary particles are known with less uncertainties (Tab. 4).

Particle	$\Delta m/m$, ppm
n	0.02
p	0.02
e	0.02
μ	0.03
$\pi^\pm$	2.5
J/ψ	3.5
ψ'	3.8
π^0	4.4

Table 4: Mass measurement accuracy. Only five particle masses are measured with higher accuracy in regard to our results on J/ψ and ψ'.

Tau lepton mass measurement was performed at the energies in vicinity of the tau production threshold where polarization at the VEPP-3 booster is not available. We could apply the RD technique in such conditions by the following way: the polarization is obtained at an energy of 80 MeV above the integer spin resonance. After injection of the polarized beam its energy is lowered down to the tau threshold. At that, the lifetime of polarization at VEPP-4M lasts out to calibrate energy by the spin frequency. The data on joint application of the RD technique and the CBS monitor in the tau mass measurement are presented above. The τ lepton mass measurement with the detector KEDR improved the accuracy of the lepton universality test.

8. Summary

Since 2002 we have performed a series of mass measurement experiments with the KEDR detector using RD technique for absolute beam energy calibration of 10^{-6} accuracy. Masses of J/ψ and $\psi(2S)$ (the best accuracy); D^0 (the second result after CLEO); $D^\pm$ (the best direct measurement), tau-lepton (the best result at present) have been measured. Application of CBS for monitoring the energy (50-100 keV) between RD calibrations and the energy spread $(7-10\%)$ in these experiments was an innovation. Touschek polarimeter used for RD at VEPP-4M works very well at $E < 2$ GeV but will be rather non-effective at $E > 4\,GeV$ because of considerable decrease of effect and counting rate with energy (we consider laser polarimeter as an alternative for possible mass measurements in the range of Υ resonance family).

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